TECHNICAL EVALUATION OF REFRIGERANT HFC-134A IN THE U.S. NAVY SHIPBOARD RECIPROCATING AIR CONDITIONING AND REFRIGERATION SYSTEMS

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ABSTRACT

As a result of global concerns over the depletion of the earth's protective stratospheric ozone layer by the atmospheric release of chloroflourocarbons (CFCs), the Montreal Protocol and other domestic/international agreements prohibited production of CFCs after December 1995. CFCs are used extensively throughout the U.S. Navy in various reciprocating refrigerant plants providing vital cooling to shipboard communications, navigation, weapon systems and food preservation. In order to prevent the CFC production ban from interfering with Fleet operations, the Navy established an aggressive program to convert existing air conditioning and refrigeration systems using CFC-12 to HFC-134a.

The intent of this paper is to provide a technical overview of converting CFC-12 reciprocating air conditioning and refrigeration systems to HFC-134a. This paper will summarize the suitability of HFC-134a for replacing CFC-12 and will present landbase and shipboard test results, as well as expand on technical developments experienced during the implementation process.

BACKGROUND

As a result of global concerns over the depletion of the earth's protective stratospheric ozone layer by the atmospheric release of chloroflourocarbons (CFCs), the Montreal Protocol and other domestic/international agreements prohibited production of CFCs after December 1995 [1,2]. CFCs are used extensively throughout the U.S. Navy in various reciprocating refrigerant plants providing vital cooling to shipboard communications, navigation, weapon systems and food preservation. In order to prevent the CFC production ban from interfering with Fleet operations, the Navy established an aggressive program to convert existing refrigerant CFC-12 air conditioning and refrigeration systems. A CFC-12 stockpile was established for Fleet use until all CFC-12 systems are converted and/or retired. The U.S. Navy has one of the largest installed bases of CFC-12 air conditioning and refrigeration systems aboard its fleet of ships. To ensure protection of the environment and preventing a negative impact on the Navy's National Defense mission [3], the NSWCCD-SSES CFC Team has provided technical expertise required to convert the Navy's CFC-12 systems to ozone-friendly HFC-134a. Under this program, over 350 Navy CFC-12 systems have already been converted to utilize refrigerant HFC-134a. A total of 1,100 Navy CFC-12 systems are planned to be converted by the year 2000.

With the vast numbers of refrigerant CFC-12 replacements available, an extensive evaluation of the many replacement refrigerants had to be performed in choosing the most cost effective replacement. Retrofitting, conversion, and even stockpiling had to be evaluated based on system condition, economic life, and associated costs. To choose an effective replacement, the refrigerant should be contained within the Environmental Protection Agency's (EPA) Significant New Alternatives Policy (SNAP) program as well as being approved by the Original Equipment Manufacturer (OEM). The replacement refrigerant thermodynamic properties had to be evaluated at design operating condition to ensure the differences in capacities, compression ratios, efficiencies and operational pressures were acceptable. Other characteristics such as toxicity, flammability, temperature glide (components of a refrigerant blend boiling or condensing over a range of temperatures), system compatibility, recovery / reclamation compatibility, refrigerant composition changes (system leaks typically changes the composition of refrigerant blends which could effect performance), ozone depletion potential (ODP), global warning potential (GWP), and motor horsepower requirements also had to be analyzed. Also considered was the fact that hydrochlorofluorocarbon (HCFC) refrigerants were subject to a future production phaseout that may be accelerated. The Navy had to weigh the advantage and disadvantage of the numerous choices in selecting an ideal replacement.

Properties of HFC-134a:

As a fluorocarbon without chlorine, refrigerant HFC-134a does not affect the ozone layer while having boiling points and chemical properties similar to refrigerant CFC-12. Refrigerant HFC-134a is less dense than refrigerant CFC-12 and has a greater refrigeration effect. To obtain comparable performance at low temperatures (below 20 degrees F), modifications are necessary to increase the compressor pumping capacity. Refrigerant HFC-134a has a significant lower global warning potential than refrigerant CFC-12 (0.25 verse 2.7 relative to CFC-11 having a base of 1). Although refrigerant HFC-134a has a low degree of toxicity, it can decompose into hazardous products (hydrofluoric acid and possibly carbonyl fluoride) at high temperatures [4].

A concern with converting the existing CFC-12 systems to refrigerant HFC-134a was the immiscibility of mineral oil with refrigerant HFC-134a. Polyol ester (POE) lubricants were identified by the air conditioning and refrigeration industry as the lubricants of choice for use with refrigerant HFC-134a. POE oil is a synthetic oil formulated from a mixture of acids and alcohols that has excellent thermo and oxidative stability. POE oil is not only compatible with refrigerant HFC-134a but also with CFC, HCFC, and other HFC refrigerants as well as mineral oil. POE oil is hygroscopic (absorb moisture) and therefore its exposure to the atmosphere should be minimized. Residual mineral oil within an HFC-134a system will adversely affect miscibility (directly proportional to the level of contamination) of the oil mixture at low temperatures that may result in a system blockage. Therefore residual mineral oil is reduced to levels that will eliminate adverse consequences during the conversion process through a series of POE oil changes.

Air Conditioning Plant Landbase and Shipboard Evaluation [5,6,7,8]:

Refrigerant HFC-134a was selected to replace refrigerant CFC-12 in an air conditioning application based on its comparable properties. A comparison of CFC-12 and HFC-134a for an ideal air conditioning plant operating cycle with a 40°F refrigerant evaporating temperature and a 100°F refrigerant condensing temperature is shown in Table 1.

Table 1. HFC-134a & CFC-12 Air Conditioning Property Comparison

REFRIGERANT DESIGNATION	CFC-12	HFC-134a
Chemical Formula	CCl_2F_2	$C_2H_2F_4$
Evaporator Pressure (psia)	51.67	48.90
Condenser Pressure (psia)	131.86	139.00
Flow Rate (ft^3/min/ton)[2]	3.07	2.99
Power (Hp/ton)[2]	0.672	0.680
Ozone Depletion Potential (ODP)[1]	1.0	0
Global Warming Potential (GWP)[1]	2.7	0.25

Note: (1) ODP and GWP are relative to CFC-11 having a value of 1.0.
(2) Data based on 40°F evaporating and 100°F condensing temperatures with 100% efficient compressor and motor.

Land-based testing at CDNSWC Annapolis Detachment as tasked by NAVSEA was performed on a 25 ton (Carrier 5MH46) and an 80 ton (Carrier 5MH126) reciprocating air conditioning systems. The plant operating conditions, cooling capacity, and power consumption were measured for each plant under design full load conditions and various partial load conditions. The Carrier 5MH46 reciprocating air conditioning plant at full load capacity yielded 24 to 26 tons as a function of superheat (8-12°F) with refrigerant HFC-134a. When compared to the baseline CFC-12 performance, HFC-134a provided a five percent increase in cooling capacity with a minimal change in power consumption. The Carrier 5MH126 reciprocating air conditioning compressor yielded 74 to 78 tons as a function of the same superheat range with refrigerant HFC-134a. When compared to the baseline CFC-12 performance, HFC-134a provided a one percent increase in capacity with a three percent increase in power consumption. Oil and refrigerant samples were periodically taken and analyzed. The compressors were also periodically disassembled to measure wear. The overall result of the landbase testing of HFC-134a in both compressors was that HFC-134a would be a viable replacement for CFC-12 shipboard air conditioning plants.

It should be noted that the Carrier 25 ton reciprocating air conditioning system utilized a polyalkyleneglycol (PAG) lubricant during the above evaluation. PAG oils are extremely hygroscopic and can absorb several thousand parts per million of water upon exposure to the atmosphere. When PAG oil is used as the lubricant, extreme care must be exercised to remove all residual CFC-12 and mineral oil from the system including replacing gaskets, valve packing, switches, gauges, etc. Residual CFC-12 contains chlorine that will react to form certain harmful acids. Residual mineral oil must be removed since it also contains residual CFC-12. Throughout the evaluation, poor oil return was encountered. After 5100 hours of operation, the compressor was disassembled and it was noticed that a piston, connecting rod and wrist pin were severely damaged. Severe copper plating was also observed. This failure and copper plating were considered characteristic of the PAG lubricant. PAG oil was not used as the lubricant for the 80 ton plant evaluation; instead polyolester oil was introduced as the lubricant for refrigerant HFC-134a.

Based on the successful landbased testing, prototype installations were performed on a frigate (FFG-7 class) and an ammunition (AE-26 class) ship by NSWCCD Philadelphia. These prototype installations were evaluated for a one year period to prove-out the suitability of HFC-134a as a replacement for CFC-12 in a shipboard environment.

The first shipboard technical evaluation was conducted on three 12 cylinder reciprocating (Carrier 5MH126) Air Conditioning systems on USS DEWERT (FFG-45) which underwent conversion February 1992 to operate with refrigerant HFC-134a. The modification package (identified during Annapolis landbased testing) included the refrigerant, lube oil and dehydrator cartridge changeout; installation of a new chill water actuated capacity control system, a lube oil cooler, lube oil heaters, a crankcase thermostat, and six electrical relays. Additionally, a compressor overhaul including the installation of steel connecting rods was performed on each air conditioning system. During the evaluation, a number of failures were experienced. None of these failures were attributed to the refrigerant but rather errors in installation and operation. After operating with refrigerant HFC-134a for a year, those three compressors had accrued over 21,000 hours of operation with refrigerant HFC-134a and polyolester oil. Quarterly oil samples revealed that residual mineral oil, moisture, acid, and wear metal levels to be acceptable. Compressor teardown of the No. 2 air conditioning system (over 4000 hours of HFC-134a operation) revealed all wear surfaces to be within manufacturer's tolerances and no copper plating was noticed. One of the two suction strainer had failed and was similar to previous failures found on CFC-12 systems.

The next technical evaluation was conducted on four 8 cylinder reciprocating air conditioning (Carrier 5MH86) systems on USS MOUNT HOOD (AE-29) which underwent conversion May 1992 to operate with refrigerant HFC-134a. The modification package was similar to that was installed on the USS DEWERT (FFG-45). Oil heater were already installed on this ship class. No major failures occurred during the evaluation period and total operational hours on all four air conditioning plants were over 10,000 hours. Quarterly oil samples had revealed that residual mineral oil, moisture, acid, and wear metal levels to be acceptable. Compressor teardown of No. 1 air conditioning system (over 4000 hours of HFC-134a operation) revealed all wear surfaces to be within manufacturer's tolerances.

With over 31,000 shipboard operational hours in addition to testing at land based test sites with HFC-134a, it was concluded that HFC-134a would be a viable replacement for CFC-12 in air conditioning application. Fleet implementation proceeded.

Refrigeration Plant Landbase and Shipboard Evaluation [9,10,11,12,13]:

Landbased testing of HFC-134a in CFC-12 refrigeration equipment was performed by the NSWCCD Philadelphia to evaluate refrigerant HFC-134a operation and determine if any deleterious effects would occur at the increased compression ratios. Table 2 gives the comparison of HFC-134a and CFC-12 for an actual refrigeration system operating at a -20^{0} F refrigerant evaporating temperature and a 105° F refrigerant condensing temperature.

Table 2. HFC-134a and CFC-12 Refrigeration Property Comparison

REFRIGERANT DESIGNATION	CFC-12	HFC-134a
Chemical Formula	CCl_2F_2	$C_2H_2F_4$
Evaporator Pressure (psia)	15.27	12.89
Condenser Pressure (psia)	141.4	149.6
Compression Ratio	9.26	11.61
Flow Rate (ft^3/min/ton)[2]	0.0576	0.0503
Power (Hp/ton)[2]	3.0348	3.1945
Ozone Depletion Potential (ODP)[1]	1.0	0
Global Warming Potential (GWP)[1]	2.7	0.25

Note: (1) ODP and GWP are relative to CFC-11 having a value of 1.0.
(2) Data based on actual refrigeration plant operation at -20°F evaporating and 105°F condensing temperatures.

Initial tests were conducted on a land-based Carrier 5F30 refrigeration plant (see Figure 1) that simulated a shipboard-type plant. The major finding quantified the average loss in capacity to be 22%. Testing also demonstrated the need for an oil cooler in Navy refrigeration plant compressors. A refrigerant-cooled oil cooler design was selected, since chilled water is not readily available to support a water-cooled cooler in many shipboard refrigerant machinery rooms. The loss in cooling capacity resulting from the installation of a refrigerant-cooled oil cooler was measured to be approximately 12%. The CFC-12 refrigerant plant once converted to HFC-134a with an oil cooler resulted in a total decrease in available capacity of approximately 34 percent. Measurements taken on the Carrier compressor internal wearing parts showed no appreciable wear after 2000 hours of HFC-134a operation at the increased compression ratios.

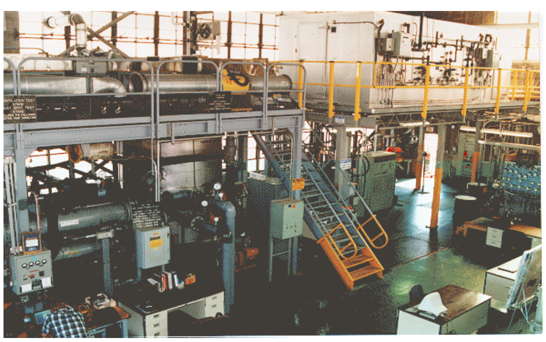

Figure 1. CDNSWC-SSES Refrigeration Test Facility

As shown in Table 3, the land base testing confirmed that the Carrier 5F30 compressor CFC-12 capacity was consistent with published ratings at 1.32 tons. When the oil cooler was placed in operation with refrigerant CFC-12, a reduction in usable evaporator capacity of 0.15 tons was experienced.

As shown in Table 4, there was a 22% reduction in capacity (to 1.02 tons) when operating using HFC-134a as the refrigerant. Lowering the saturated discharge temperature to 100°F increased the capacity to 1.09 tons. There was a reduction of 0.15 tons (12%) in usable evaporator capacity with the oil cooler in operation when using HFC-134a as the refrigerant, which was consistent with CFC-12 baseline operating data. Operation with the liquid/suction heat exchanger bypassed reduced the capacity to 0.96 tons using HFC-134a.

Table 3. CFC-12 Baseline

RUN	SST (°F)	SDT (°F)	Oil Cooler Status	HP/Ton	Usable Tons
BASELINE HH	- 20	105	OUT	3.02	1.32
BASELINE II	- 20	105	IN	3.06	1.17

SST - Saturated Suction Temperature
SDT - Saturated Discharge Temperature

Table 4. HFC-134a Test Runs

RUN	SST (°F)	SDT (°F)	Oil Cooler Status	HP/Ton	Usable Tons	% Loss
R-134a EE	- 20	105	OUT	3.16	1.02	22
R-134a FF	- 20	100	OUT	3.00	1.09	17.5
R-134a GG	- 20	105	IN (142°F Oil)	3.23	0.87	24
R-134a II	- 20	100	IN (139°F Oil)	3.06	0.94	--
R-134a JJ	- 20	105	IN (148°F Oil)	3.20	0.84	28
R-134a LL	- 20	100	IN (148°F Oil)	3.03	0.93	--
R-134a BB	- 15	105	OUT	2.91	1.32	0
R-134a HTEXBPA	- 20	105	OUT	3.41	0.96	27
R-134a HTEXBPB	- 20	105	IN	3.45	0.83	29

SST - Saturated Suction Temperature
SDT - Saturated Discharge Temperature
Run HTEXBPA and HTEXBPB was performed with the heat interchanger bypassed.

Upon successful testing of the Carrier Model 5F30 compressor, a York Model F series three cylinders compressor was tested with refrigerant HFC-134a. Compressor HFC-134a capacity was verified at 1265 rpm (operating speed of the FFG-7 class CFC-12 refrigeration system) and at 1750 rpm. Operation of the compressor

(SST of -20^{o}F and SDT of 105^{o}F) at 1265 rpm without an oil cooler yielded a usable evaporator capacity of 0.82 tons. Operation of the compressor (SST of -20^{o}F and SDT of 105^{o}F) at 1750 rpm without an oil cooler yielded a usable evaporator capacity of 1.12 tons. These results confirmed that the York FN32 compressor experienced comparable HFC-134a losses when compared with the OEM published FN32 compressor capacity ratings. The results also showed that raising the operating speed from 1265 rpm to 1750 rpm would offset expected capacity losses that occur from refrigerant HFC-134a at refrigeration operating temperatures. After a 2000 hour endurance test, compressor teardown revealed no elongation of the aluminum connecting rods and the only significant wear occurred within the inner discharge valve seat. Consequently, this inner seat would be replaced with one manufactured from a harder material during the HFC-134a conversion of York F series refrigeration systems. York R series compressors were already equipped with the harder inner discharge valve seat.

After quantification of the refrigerant HFC-134a capacity loss with an oil cooler (34 percent), theoretical evaporator loads were calculated and compared with the expected HFC-134a compressor capacity for each ship class expected to be converted to HFC-134a [14]. Fortunately, most of the Navy's shipboard refrigeration compressors were originally oversized, and therefore could be modified to operate with refrigerant HFC-134a with no need to change the compressor pumping rates. For those shipboard refrigeration systems not initially oversized, some of these systems' compressor capacity could be easily increased to provide the necessary evaporator capacity by increasing the compressor speed. Other systems would require the installation of a larger compressor to provide the necessary capacity.

Upon successful land-based testing of refrigeration systems, NSWCCD-SSES was tasked by NAVSEA to perform a shipboard evaluation of refrigerant HFC-134a in both York and Carrier reciprocating refrigeration plant for a one year period. These evaluations were performed to prove HFC-134a to be a viable refrigerant alternative in refrigeration applications.

In September 1993, the two 3-cylinder York Model "F" series refrigeration units on USS DEWERT (FFG-45) underwent conversion to operate with refrigerant HFC-134a . During the conversion, the existing motor pulley was replaced to increase the compressor speed from 1265 revolutions per minute (rpm) to 1750 rpm. This variation in speed increased the compressor pumping capacity, compensating for the capacity loss experienced with HFC-134a (saturated suction temperature of -20 degrees F and a saturated discharge temperature of 105 F). The conversion consisted of replacing the thermal expansion valves, installing an oil cooler, replacing the dehydrator cartridges to be HFC-134a compatible, replacing the compressor inner discharge valve seats, replacing the evaporator fans, and charging the plant with an HFC-134a compatible POE oil. During the one year evaluation, these refrigeration systems accrued over 5600 hour of shipboard operation while maintaining design evaporator temperatures. Quarterly oil samples revealed viscosity, residual mineral oil, water, acid, and wear metals levels to be within acceptable limits and compressor teardown showed no significant compressor wear.

In May 1994, the two 6-cylinder Carrier Model "5MF" series refrigeration units on USS MOUNT HOOD (AE-29) underwent conversion to operate with refrigerant HFC-134a. Since these compressors were originally oversized, no speed change was required to compensate for the capacity loss experienced with refrigerant HFC-134a. The conversion consisted of replacing the thermal expansion valve, installing an oil cooler and heater, replacing the dehydrator cartridges to be HFC-134a compatible and charging the plant with an HFC-134a compatible POE oil. During the one year evaluation, these refrigeration systems accrued over 5970 hours of shipboard operation while being capable of maintaining design evaporator temperatures. System contamination had caused several of the system's filters and thermal expansion valves to clog, and also prevented the compressor internal suction and discharge valves from properly seating throughout the evaluation. These conditions resulted in elevated evaporator temperatures until the problem was corrected. Analysis of the contamination collected within this system revealed organic and inorganic debris. The inorganic portion was primarily iron oxide (rust) and copper with minimal presence of chloride, nickel, silicon, phosphorus and potassium. The organic portion was an amber, varnish-like sludge. Infrared analysis of the organic portion revealed the presence of esters, organic acids and metallic soaps. Typically these compound results from overheating of oil and are sticky in nature. It should be noted that this system had been contaminated prior to the HFC-134a conversion as evident by past refrigerant usage, past oil samples revealing high moisture and acid content, carbonization of internal compressor components (indicating past operation at high operating temperatures), and elevated evaporator temperatures. During the compressor teardown, no unusual wear was visually observed, but a slightly accelerated wear of the compressor's bearing surfaces was measured and theorized to be caused by oil contamination. Quarterly oil samples revealed viscosity, residual mineral oil, water and acid levels to be acceptable, while high levels of wear metals were detected.

With over 11,570 shipboard operational hours and more at land based test sites with HFC-134a, the Navy concluded that HFC-134a would be a viable replacement for CFC-12 in shipboard refrigeration systems. Fleet implementation proceeded.

Air Conditioning and Refrigeration HFC-134a Procedures and Modifications

An accurate and thorough assessment of the applicable refrigerant system is performed prior to (three to six months) the conversion. The results of these inspections are used to determine the material condition of the system and the feasibility of performing the alteration within the allotted time period with the available manpower. It is Ship's Force responsibility to correct all system discrepancies that are not within the scope of the alteration prior to the commencement of the alteration. Arrangements are sometimes made for any repairs that should be performed when the refrigerant is removed from the system. Common repair parts are also staged to help prevent delays in the contractor work from unavailability of parts.

When retrofitting a CFC-12 system to refrigerant HFC-134a, mineral oil is drained from the compressor crankcase and the system is charged with POE 68 CST oil. All of the system's filters/strainers are cleaned/replaced and felt socks inserted into both the liquid line and suction strainers. The system is then operated at full load conditions with refrigerant CFC-12 while valves in dead legs are carefully cycled. The POE / mineral oil mixture is drained and the compressor charged with virgin POE oil. This process is repeated until the residual mineral oil is reduced below the maximum recommended concentration (one percent for a refrigerant system and four percent for an air conditioning system). A refractometer is often used to track the reduction in residual mineral oil concentration. This method compares the original refractive index of the mineral and POE oil with that of the oil mixture to determine the percentage of residual mineral oil. Commercial test kits are used to verify the residual mineral oil concentration has been reduced to an acceptable level by visually observing the oil mixture being mixed with a solvent.

While the process of reducing the mineral oil concentration is in progress, the system material condition is evaluated to ensure reported discrepancies have been corrected and parts are available for any existing discrepancies. Next, refrigerant CFC-12 is recovered from the system in accordance with EPA guidelines. The system is maintained under a dry nitrogen blanket while further work and repairs are accomplished.

The existing dehydrator cartridges are replaced with filter drier cartridges using molecular sieve XH-7 or XH-9 in all air conditioning and refrigeration (A/C & R) conversions. These filter drier cartridges are constructed with an inner molded desiccant core for filtering with the remainder of the cartridge containing loose desiccant. Molecular sieves XH-7 and XH-9 offer superior properties with refrigerant HFC-134a (see Table 5) and are also compatible with other refrigerants such as CFC-11, CFC-12, and CFC-114. Some molecular sieve were found to be unsuitable such as 4A-XH-6, which is compatible with refrigerant HFC-134a but has a high hydrated attrition (seven percent by weight). Attrition is the tendency of a beaded desiccant to form fine particles from abrasion action from flow and vibration. Molecular sieve 4A-XH-5 will actually absorb refrigerant HFC-134a molecules instead of moisture and is unsuitable. Some existing models of solid core dryers are compatible with refrigerant HFC-134a. The drier manufacturer should be consulted for their recommended drier for use with refrigerant HFC-134a.

Table 5. Properties of HFC-134a Compatible Molecular Sieves [15]

Molecular Sieve	4A-XH-6	XH-7	XH-9
Bead Size	2 mm	2 mm	2 mm
Water Capacity 4.6 torr, typical	17.5 wt %	17.0 wt %	16.0 wt %
Density, min	50 lb/ft3	53 lb/ft3	53 lb/ft3
Crush avg. 25 beads, min	10 lb.	12 lb.	12 lb.
Dry Attrition, Max	1.0 wt %	0.7 wt %	0.7 wt %
Hydrated Attrition, Max	7.0 wt %	2.0 wt %	2.0 wt %

The compressor's shaft seal, gaskets and o'rings must be chemically compatible with refrigerant HFC-134a and polyolester oil. The Navy has requested that HFC-134a compressors be equipped with HFC-134a compatible elastomers. Sealed tube testing revealed Fluroroelastomers (such as Viton A, Viton B, Viton GF, and fluorinated silicones) and gasket material cork are incompatible with refrigerant HFC-134a [16]. Furthermore, Natural rubber and Vernac EA are incompatible with polyolester oil while Nordel EPDM is borderline [17]. To date, the preferred elastomers for refrigerant HFC-134a systems are Neoprene CR, Butyl rubber, and Nitrile rubber.

All A/C & R compressors utilizing refrigerant HFC-134a are being equipped with oil heaters if not already installed. Whenever the compressor motor is deenergized, the crankcase oil heaters increase the temperature of the polyolester oil to reduce the percentage of dissolved refrigerant HFC-134a in the crankcase oil. This is done to prevent polyolester oil from becoming saturated with refrigerant HFC-134a which will create a more violent reaction in the compressor than would a mixture of refrigerant CFC-12 and mineral oil, which may result in a vapor lock within the crankcase oil passages. Reducing the quantity of dissolved refrigerant HFC-134a in the POE oil will also increase the lubricity and viscosity of the lubricating oil.

All A/C & R compressors utilizing refrigerant HFC-134a are also being equipped with an oil cooler to prolong the life of the shaft seal. To prevent accelerated wear and eventual failure of the compressor shaft seal, OEMs typically recommend the shaft seal housing temperature remains below 180 degree Fahrenheit. A temperature control valve is being installed to modulate either refrigerant HFC-134a or chilled water through an oil cooler, thus maintaining the crankcase oil temperature at an acceptable value.

Most of the refrigeration system's thermal expansion valves will require power assembly replacement when converted to refrigerant HFC-134a. No power assembly changes are required on air conditioning systems. The existing power assemblies in refrigeration systems are operating in a temperature range not recommended by the OEM and greater superheat fluctuation was observed using refrigerant HFC-134a. "Maximum operating pressure" power assemblies are being utilized with refrigerant HFC-134a which are suitable for both freeze and chill application. Another difference with TXVs using refrigerant HFC-134a is an increase in the valve's overall capacity. This increase is caused by a greater net refrigeration effect with refrigerant HFC-134a as well as the increased flow from operating at greater pressure differential. Comparing the extended capacity tables for TXVs has quantified this increase in valve tonnage to be approximately 20 to 40 percent [18]. Actual capacity increases will depend on actual operating conditions. If the TXV is not adjusted, the superheat will be less for a refrigerant HFC-134a system than the previous CFC-12 system. Where the TXVs are drastically oversized, the internal cages are being replaced to reduce the valve capacity and thereby maintain better superheat control.

When a Navy refrigeration system is converted to utilize refrigerant HFC-134a, two speed circulating fans are installed to increase heat transfer via increased airflow within freeze boxes containing gravity coils. These fans are not installed within systems having vaned axial fans or unit coolers since the airflow is already more than adequate. These fans are to be operated on low speed within chill application (33^{o} F) since increased airflow may accelerate the dehydration of fruits and vegetables. These fans are to be operated on high speed during freeze applications. Gravity coils are typically sized to maintain design evaporator temperatures with a 20 degree temperature differential (TD). A one degree change in the TD typically affects the capacity by 3 to 5 percent. These fans will lower the evaporator TD, which increases both the volumetric efficiency and capacity of the compressor.

There are several items being accomplished during the conversion process to improve the reliability and maintainability of the air conditioning and refrigeration systems. For example, vibration eliminators are being installed in various ship classes to prevent stress fatigue of, and vibration transmission of refrigerant piping. Additionally, a chilled water actuated capacity control system with six control relays is being installed on reciprocating air conditioning systems to provide better control of the chilled water outlet temperature and to aid in preventing floodback.

After all of the above components are installed and repairs are accomplished, a system pressure test is conducted with refrigerant HFC-134a and dry nitrogen. After all leaks are repaired, a triple evacuation is performed in which vacuum levels of 5 mm Hg are held during each evacuation. Extreme care is exercised during these evacuations to remove residual refrigerant CFC-12 and moisture from the system. The system is then charged with refrigerant HFC-134a. Since refrigerant HFC-134a is less dense than CFC-12, the optimum HFC-134a charge will be approximately 90 percent of the original CFC-12 charge weight. Applicable system's controls (thermal expansion valves, compressor capacity controls, water regulating valves, temperature control valves, and control switches) are adjusted for optimum HFC-134a operation.

Refrigerant Leak Detection Methods

In response to the CFC Elimination Program need to reduce leaks in Navy air conditioning and refrigeration systems, NSWCCD Philadelphia performed an evaluation of commercially available refrigerant leak detection methods/equipment. This would allow the Fleet to reduce refrigerant losses in air conditioning and refrigeration systems by using better detection equipment. This evaluation was also necessary due to Fleet introduction of refrigerant HFC-134a, which required detectors with greater sensitivity than those used to detect CFC refrigerants presently used. Commercial hand held leak detectors and oil miscible fluorescent dyes were evaluated. The following paragraphs in this section provide further detailed information about the two types of leak detection methods and equipment evaluated.

A variety of hand-held refrigerant leak detectors were tested and evaluated to find the best detector in terms of accuracy, repeatability, portability and ease of use [19]. The main testing criterion was to be able to detect a 0.5 ounce per year (or greater) CFC and HFC leak rate in both a 0 ppm and a 1000 ppm refrigerant background. There were two methods of detecting hologenated refrigerants being utilized by commercial detectors. The “corona discharge” method involves applying a voltage between two electrodes, thus producing an electrical arc that is extinguished in the presence of halogenated refrigerants. The “heated diode” method is an emitter and heated collector to sense an increase in diode current in the presence of a halogenated refrigerant. Testing revealed the “heated diode” technology to be far superior to the “corona discharge” technology. Most leak detectors approved for multi-refrigerant detection contain an CFC and HFC position switch since, as mentioned earlier, greater sensitivity is required to detect HFC refrigerants.

Oil-miscible dyes that fluoresce under ultraviolet (UV) light were tested and evaluated to determine suitability for use in shipboard air conditioning and refrigerant systems as an alternative leak detection method [20]. This leak detection method typically consists of oil miscible dye, UV lamp, UV-protective eyeware and dye injection equipment. Once the dye is injected in a system, the dye/oil mixture tends to pool at refrigerant leakpoints. When these leakpoints are exposed to UV light, leaks are quickly pinpointed by the dye’s eye-catching fluorescence. Many brands of POE oils contain additives that will also fluoresce with UV light but the injection of the dye will intensify this fluorescence. Different manufacturers of the UV-dye were evaluated based on cost, spectrofluorometer emissions, and excitation spectra measurements. Sealed tube testing was accomplish to determine the stability and compatibility of the UV-dye with typical air conditioning and refrigeration systems. A series of POE and mineral oil samples containing UV dye showed that no detrimental physical/chemical effects would be experienced during the Navy Oil Analysis Program (NOAP) testing. The UV lamps were evaluated based on UV light irradiance and visible light intensity at various environmental conditions. Testing concluded that UV leak dyes can be used as a viable leak detection method in air conditioning and refrigeration systems. This method was added to the Planned Maintenance Schedule, and several advisories [21,22] have been issued to provide guidance in procuring and using the approved UV-dye kits.

LESSONS LEARNED

There have been a number of lessons learned from the HFC-134a conversion program. Below is a synopsis of those most noteworthy :

Most important was maintaining the cleanliness of the system following conversion. Both refrigerant HFC-134a and POE oil are better cleansing agents than refrigerant CFC-12 and mineral oil. Consequently, this HFC-134a/POE oil combination dissolves and dislodges particles that had previously deposited and accumulated during refrigerant CFC-12 operation. Dislodging of these contaminants (carbonized mineral oil; iron, carbon, and aluminum oxidation; etc.) has degraded the system operation by contaminating the crankcase oil as well as clogging expansion devices and other system filters/strainers. To remove those contaminants, a six month maintenance program has been implemented. Felt socks are used to increase filtration efficiency. In a refrigeration system (where contamination is usually more severe), the existing liquid line strainers upstream of the TXVs are being replaced with a solid core filter-dryer to increase filtration efficiency.

Of great importance also was the need to locate and repair low side leaks within refrigeration systems in a timely manner. HFC-134a refrigeration systems operate in a deeper vacuum on the suction side than CFC-12 systems. This deeper vacuum causes more air and moisture to enter the system from low side leaks. Moisture will promote acid development within the system and may cause erratic operation of the TXV if moisture freezes at the TXV and restricts refrigerant flow. The moisture and acid will cause chemical instability within the system and may cause other system components to malfunction.

Additionally, mixing of refrigerants must be avoided but can occur. If refrigerant HFC-134a and CFC-12 are mixed, an azeotrope is formed [23]. An azeotrope is a mixture of two or more refrigerants that form a single refrigerant compound having physical and chemical properties independent of the independent refrigerants. Refrigerant HFC-134a and CFC-12 will form a high pressure azeotrope having a higher vapor pressure than either of the two individual components. Table 6 shows pressures of CFC-12 / HFC-134a mixtures at typical saturated conditions. This could result in more frequent high pressure and motor overload shutdowns, as well as inefficient system performance from operating with mismatched compressor control setpoints. Azeotropes are difficult to separate the individual components once mixed. Such mixtures usually have to be disposed of by incineration.

Table 6. Pressures of CFC-12 / HFC-134a mixtures at typical saturated conditions

% CFC-12 by weight in HFC-134a	Pressure (psia) -20 degrees F	Pressure (psia) 35 degrees F	Pressure (psia) 105 degrees F
0	12.96	45.05	149.7
10	14.1	47.75	155.4
20	15.04	50.01	160.1
30	15.83	51.86	163.5
40	16.5	53.25	165.5
50	17.0	54.09	166.0
60	17.24	54.22	164.7
70	17.19	53.51	161.6
80	16.83	52.21	156.6
90	16.19	50.1	149.9
100	15.35	46.89	139.9

Note: The above properties of the CFC-12 / HFC-134a mixture was calculated using NIST Thermodynamic Properties of Refrigerant Mixtures [24].

Finally, use of mineral oil in a refrigerant HFC-134a system must be avoided. This too is likely to occur. If mineral oil is accidentally added to an HFC-134a system, the oil may restrict flow causing the refrigerant to sputter as it passes through the dehydrator and thermal expansion valve(s). Once in the evaporator, the immiscible mineral oil may settle on the internal surface of the evaporator further reducing cooling efficiency by decreasing heat transfer rates. In a severe case, lack of oil return to the compressor will accelerate wear and possible compressor failure through lubrication starvation. Mineral oil in circulation may experience difficulties returning from the evaporator to the crankcase. The presence of mineral oil may be remedied by operating the refrigerant system at full load or pulldown conditions while performing a series of POE lubricant changes. Increased suction gas velocity will promote oil return by transferring momentum to the immiscible oil droplets. In a severe case of mineral oil contamination, the immiscible mineral oil must be removed at low spots within the system. A series of POE lubricant changes may be required using a miscible refrigerant such as CFC-12.

ACCOMPLISHMENTS

The NSWCCD-SSES CFC Team has successfully converted over 435 air conditioning and refrigeration systems aboard U.S. Navy ships and Army Water Craft. This resulted in there now being over 150 "CFC-12 Free" ships around the world, with a total installed charge in excess of 48 tons of CFC-12.

In 1995, twenty-seven Air Conditioning and Refrigeration systems aboard three Taiwanese frigates were converted from CFC-12 to HFC-134a with technical assistance from NSWCCD-SSES. In 1996, NSWCCD-SSES expertise was formally exported across the Pacific to Taiwan in the form of detailed technical documentation allowing the Taiwanese to convert their Fleet to HFC-134a.

The NSWCCD-SSES CFC Team also exported its expertise to Europe in June of 1996 and converted the Spanish frigate CANARIAS (F86). Using a special team (complete with conversion kits, procedures, and a translator), NSWCCD-SSES converted the ship's air conditioning and refrigeration systems. Local technicians were trained to convert the remainder of the Spanish Fleet.

In addition to assisting foreign Navies, NSWCCD-SSES CFC Team has provided assistance and recommendations to the U. S. Army required to convert air conditioning and refrigeration systems aboard 101 Army vessels to ozone-friendly refrigerants. The U. S. Coast Guard and MSC have also received our technical guidance concerning the conversion of their CFC-12 systems to ozone-friendly alternatives.

During initial testing of the refrigerant HFC-134a in the submarine life support (air revitalization) systems, decomposition products beyond acceptable levels were encountered which required further landbase testing. The NSWCCD-SSES CFC Team including the Naval Research Laboratory has concluded through extensive land-based and shipboard testing that the carbon monoxide/hydrogen (CO/H_2) burner operational temperature would need to be lowered to obtain acceptable decomposition levels of refrigerant HFC-134a with no adverse effects on trace contaminant levels [25, 26]. All data collected indicated refrigerant HFC-134a to be an acceptable substitute for CFC-12 on submarines. The conversion will affect three pieces of shipboard equipment. First, the CFC-12 refrigeration plant will be converted to utilize refrigerant HFC-134a. Secondly, the CO/H_2 burner operational temperature and safety alarm temperatures will be lowered. Thirdly, the Central Atmospheric Monitoring System (CAMS) will also be modified to detect refrigerant HFC-134a. USS BOISE (SSN-764) is the first submarine to be converted to utilize refrigerant HFC-134a occurring fourth quarter Fiscal Year (FY) 97. A conversion package is also being developed for OHIO Class submarines with the prototype conversion scheduled for FY-98.

The NSWCCD-SSES CFC Elimination Team has made a major impact on the Fleet-wide, air conditioning and refrigeration conversion programs. They have effectively transferred this technology to the U.S. Navy, foreign Fleets and the private sector. From the Gulf of Mexico to the Pacific Northwest and the South China Sea, the NSWCCD-SSES CFC Team's expertise is reaching around the globe and making the Navies of the World ozone friendly.

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